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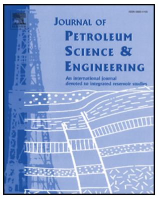

Evaluation of cement sheath integrity subject to enhanced pressure

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ABSTRACT

Well-cementing (cementation) is an influential stage of a wellbore completion, as the cement sheath is responsible for providing a complete zonal isolation. Therefore, it is of utmost importance to understand the cement mechanical failure mechanisms since well cement failure and interfacial debonding between the cement and casing and cement and rock formations can lead to a barrier failure. During the wellbore lifetime, a cement sheath is subjected to pressure loading variations. This paper demonstrates the results of an experimental-numerical study to investigate the cement sheath integrity after being subjected an enhanced pressure. A constitutive model specifically formulated for the modelling of quasi-brittle materials is applied to the investigation of cement sheath integrity, incorporating both compression and tensile damage mechanisms. Laboratory experiments are carried out to obtain strength properties of cement class G followed by calibration of the model parameters based on the obtained experimental results. A three-dimensional finite element framework employing the constitutive model for cement sheath and a surface-based cohesive behaviour for the interfaces is developed for integrity investigations. The effects of different orientations of in-situ stresses, different stiffness's of surrounding rock, and the eccentricity of the casing within the wellbore on the integrity of the cement and interfaces are investigated. The significance of cement sheath centralisation and elevated risk of cement mechanical failure caused by wellbore operations in anisotropic fields with soft rocks formation were highlighted. Furthermore, the relatively high magnitude of tensile damage (cracking index) within the cement sheath confirms the importance of tensile properties to be incorporated into the constitutive modelling.

1. Introduction

Four million onshore hydrocarbon wells have been drilled worldwide (Davies et al., 2014), with nearly 10000 in Australia alone (from data retrieved from Geoscience Australia) (Davies et al., 2014). The cement placed in the annular gaps between casing strings and the formation is a key barrier to provide zonal isolation and maintain the integrity of the wellbore (King and King, 2013). The integrity of the annular cement and cement interfaces has the potential to be compromised in each of the wellbore operations, including but not limited to, continuous drilling operations, completion operations, stimulation treatments, pressure integrity testing (PIT), and production processes (Heathman and Beck, 2006). Therefore, understanding of cement failure mechanisms under different operating conditions is of the utmost importance for better assessment of wellbore integrity.

Failure of the cement sheath within a wellbore is affected and governed by material mechanical properties (cement compressive strength (Ravi et al., 2002; Bosma et al., 1999; Shahri et al., 2005), Young's modulus (Ravi et al., 2002; Bosma et al., 1999; Shahri et al., 2005), tensile strength (Griffith et al., 2004), and bond strength (Gray et al., 2009)), loading conditions (in-situ stresses (Bosma et al., 1999; Griffith et al., 2004; Li et al., 2010)), cement history (cement shrinkage) (Bois et al., 2010), and also wellbore architecture (cement sheath diameter, formation properties, cement sheath eccentricity, and wellbore deviation (Bois et al., 2010; Wang and Taleghani, 2014)).

Mechanical integrity models investigated to this point can be categorised into analytical models and numerical models. Analytical methods are generally performed by applying simplified assumptions to facilitate finding solutions. The accuracy of analytical models and subsequently their solutions are limited to the correctness and suitability of their initial assumptions and simplifications. Thiercelin, Baumgarte and Guillot (Thiercelin et al., 1998) modelled the stress state within the cement sheath assuming the linear-elastic properties for cement, axisymmetric geometry, and fully bonded or unbound situations for the interfaces. Shi, Li, Guo, Guan and Li (Shi et al., 2015) estimated the initial radial and tangential stresses at cementing interfaces with the assumption of axisymmetric geometry, isotropic horizontal in-situ stresses and elastic properties for the cement sheath and interfaces. Honglin, Zhang, Shi and Xiong (Honglin et al., 2015) proposed a model using Mohr-Coulomb criterion and multi-layer thick wall

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theory assuming plane strain conditions, and all the wellbore components are deemed as thick-walled cylinders and completely bonded. However, some of these assumptions and simplifications may lead to unrealistic results. For instance, failure modes in all directions would not be captured in two-dimensional models (plane strain), and the axisymmetric geometry and assumed isotropic in-situ stresses do not correctly reflect the real conditions.

Numerical modelling can be very advantageous regarding its ability to incorporate material non-linearity, different types of geometry and boundary conditions, and in-situ stress conditions (Gray et al., 2009). The accuracy of these numerical models is reliant on the validation and verification of experimental data.

Nabipour, Joodi and Sarmadivaleh (Nabipour et al., 2010) simulated downhole stresses using FEM along with sensitivity analysis on casing internal pressure, anisotropic horizontal in-situ stresses, and casing eccentricity. They have used a plain strain model with thermo-elastic material properties and the interfaces are assumed to be fully bonded. Wang and Taleghani (2014) performed three-dimensional poroelastic simulations to assess the integrity of the cement sheath around wellbores. The interfaces have been modelled using porous cohesive elements. The cohesive parameters were determined by running inverse analyses on the bonding studies carried out by Evans and Carter (1962). Despite, the massive progress regarding interface modelling, the use of elastic behaviour for cement sheath is an over-simplification that can affect the accuracy and reliability of the results.

Fleckenstein, Eustes and Miller (Fleckenstein et al., 2000) employing a von-Mises criteria, they demonstrated that the magnitude of tangential stresses would be greatly decreased if the cement sheath acts as a ductile material with lower Young's modulus and higher Poisson's ratio which is in agreement with Goodwin and Crook (1992). The lack of pressure dependency of the von Mises criteria is however problematic in modelling cementitious materials. To overcome this shortcoming, a number of researchers have adopted the Mohr-Coulomb criteria in their work.

Bosma, Ravi, van Driel and Schreppers (Bosma et al., 1999) used a two-dimensional model considering symmetry geometry for the wellbore. Mohr-Coulomb plasticity combined with smeared cracking description was used to model the cement sheath under compression/shear and tension. The cement sheath interfaces were modelled using interface elements applying a coulomb friction criterion. Nygaard, Salehi, Weideman and Lavoie (Nygaard et al., 2014) performed an experimental-numerical study using Mohr-Coulomb plasticity model for the cement and formation to investigate the effect of dynamic loading on wellbore leakage. Their parametric study showed that cement with higher Young's modulus and Poisson's ratio are detrimental factors causing radial fractures, tensile failure and debonding. However, utilising cement with low strength mechanical properties increases the risk of shear failure within the cement sheath.

The Mohr-Coulomb model assumes a linear relationship between $\sqrt{J_2}$ and I_1 in the meridian plane, while this relationship has been experimentally shown to be non-linear (Ansari and Li, 1998; Imran and Pantazopoulou, 1996), for cementitious materials, particularly at low confinement. The major principal stress σ_1 and intermediate principal stress σ_2 are defined independently in Mohr-Coulomb model which results in underestimation of yield strength of material and, it is not in a good agreement with experiments in which the effect of σ_2 is being considered. The shape of yield surface in the deviatoric plane is an asymmetrical hexagon, whereby the sharp corners can hinder convergence in numerical simulations (Dorris and Nemat-Nasser, 1982; Jiang and Xie, 2011). Moreover, quasi-brittle materials experience a huge volume change due to large amount of inelastic strains (dilatancy) which has been overlooked so far by using associated flow rules in the modelling of the cement. The associative plastic flow rules tend to lead to poor results in dilatancy evolution (Lee and Fenves, 1998a).

The use of the modified Cam-Clay model has been suggested as a method to incorporate cement micro cracking mechanisms by Bois, Garnier, Rodot, Sain-Marc and Aimard (Bois et al., 2011) owing to the nonlinearity of stress-strain curve achieved from the isotropic drained compression tests (Ghabezloo et al., 2008) and heterogeneous nature of cement at the microscale. Although important aspects of materials behaviour (material strength, compression or dilatancy, and critical state of elements under high distortion) are considered in this model, the tensile post-peak material is not incorporated into this framework.

Numerical modelling has been significantly improved regarding complexity and ability to model wellbore integrity assessment with a high degree of accuracy. The incorporation of appropriate material constitutive law, particularly with regards to cracking behaviour, and consequently the evolution of corresponding constitutive parameters still requires attention. Bosma, Ravi, van Driel and Schreppers (Bosma et al., 1999) advocated the used of smeared cracking models in combination with plasticity and Salehi (2012) have employed a discrete crack methodology via the use of nonlinear fracture mechanics for cohesive cracks. Therefore, in this study, the concrete damage plasticity (CDP) model (Lubliner et al., 1989; Lee and Fenves, 1998b) was used to investigate cement mechanical failure. This model incorporates a non-associative flow rule and damage under both tensile and compressive stress states, which is more appropriate for the characterisation of cementitious materials.

This paper is organised as follows; Section 2 describes cement constitutive modelling including the experimental procedures to achieve mechanical properties, the concrete damage plasticity model as the appropriate constitutive model to be utilised, and the calibration of the model parameters according to the performed experiments. Surface-based cohesive behaviour is introduced for interface modelling and followed by determination of cohesive model parameters in section 3. Section 4 describes finite element modelling including model components, material properties, geometry and discretisation, initial and boundary conditions. Section 5 describes the results of cement sheath and the interfaces integrity investigations for the different initial state of in-situ stresses followed by conclusion in section 6.

2. Cement constitutive modelling

Portland Class G (API rating) well cement is predominantly utilised as the basis of well cement blends (Dusseault et al., 2000), additives are incorporated to obtain certain properties such as enhanced strength or reduced weight (Dusseault et al., 2000). In general, the permeability of cement used in oil and gas industry (cement class G) is very low usually less than 0.1 mDarcy (Lecampion et al., 2011). Therefore, hydraulic isolation will be achieved, and any probable leakage pathways can be created only through flaws resulting from issues in cement placement procedures or mechanical failure due to the variation of pressure during wellbore operations.

2.1. Experimental procedures

The concrete damage plasticity model (CDP) has been calibrated and verified according to the experiments have been performed by Arjomand, Bennett and Nguyen (Arjomand et al., 2016). The specimens were cured at 30^0C for 28 days in a pre-heated water tank with a manageable thermostat. The slurry density was 1.9 g/cc corresponding to water to cement mass ratio of 0.44. Prior to testing, the surface of samples were ground to obtain smooth ends, so the ends were perfectly orthogonal to the longitudinal cylinder axis (Imran and Pantazopoulou, 1996).

In this study, relatively slender cylindrical specimens were employed to avoid problems with platen restraint that are encountered using squat cube specimens (Teodoriu et al., 2016). The uniaxial strength measured using sufficiently slender specimens is usually around 70%–90% of the cube strength (Kong and Evans, 2014). The uniaxial compressive strength was determined using 42 mm diameter, 100 mm long cylindrical specimens which deliver aspect ratio of 2.4. It